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α-, β- and γ-Spectroscopy

STUDIES OF SOME NUCLEAR PROPERTIES AND DECAY MODES OF RADIOACTIVE NUCLEI

SÖREN TÖRNKVIST

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STUDIES OF SOME NUCLEAR PROPERTIES AND DECAY MODES OF RADIOACTIVE NUCLEI

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by

SÖREN TÖRNKVIST
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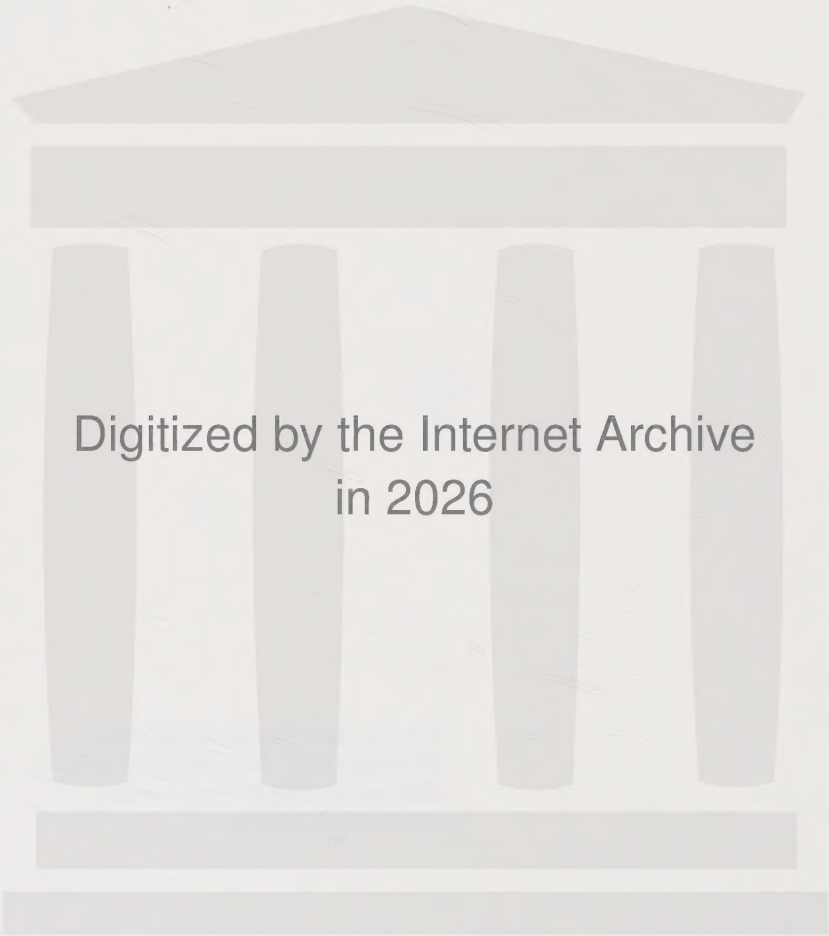
To my two lively daughters,
Rebecka and Åsa, without whom
this work might have been
completed earlier.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"Verkliga nyheter kommer oregelbundet och stötvis . . ."

Lars Gustafsson, En resa till jordens medelpunkt.

The atomic nucleus constitutes the most complicated many body system facing physics today. Besides being the only system in which all the known natural forces act simultaneously, it is also the most difficult system to handle theoretically. Not only is the principal nuclear force, the strong interaction, little or even unknown but also, the techniques of dealing with a system which is neither a few body problem such as elementary particle physics, or an extreme many body problem such as the solid state or plasma physics are not fully developed.

Historically the interplay between experimental findings and the theoretical forming of ideas and concepts resulted in different models which could account for at least some nuclear phenomena. The two extremes are the shell model and the collective model based on opposite assumptions, viz. a spherical average potential for the nucleons and a permanent deformed nucleus executing collective motion, respectively. Attempts were, however, made to unify these different approaches, e.g. the shell model for deformed nuclei by Nilsson (1) predicting intrinsic single particle levels which have been experimentally indentified.

By applying the theory of superconductivity to the nuclear system the concept of pairing was introduced to account for the residual forces between the nucleons, i.e. that part of the nucleon-nucleon force which is not represented by an average potential. The introduction of the static nuclear field, which for a spherical system is connected to the shell model, and the pair correlations defines the particle modes which are called quasiparticles. The dynamical aspects of the quasiparticle interactions are treated, at least for even-even nuclei, by introducing the collective vibrational modes called phonons, which are associated with a long range quadrupole force in addition to the short range force responsible for the pairing.

It has been shown that the competition between the deforming effect of the quadrupole force and the spherifying effect of the pairing force is responsible for the fact that some nuclei are deformed and others spherical. This development of nuclear theory,

due at least partly to Kisslinger and Sorensen (2) and Baranger and Kumar (3), means that the fundamental input in nuclear theory nowadays is a nucleon-nucleon interaction represented by a two body force.

The fact that this pairing plus quadrupole technique can account for some phenomena earlier interpreted in terms of semi-empirical nuclear models, although based on a microscopical approach, seems to bridge the gap between nuclear matter theory and the nuclear models.

The understanding of the nucleus is, despite large progress, far from complete. Much more experimental information is needed. One important means to obtain this information is to investigate the decay modes of radioactive nuclei. This thesis is mainly devoted to the study of the angular distribution of the decay products from excited nuclei. The directional correlation method by means of the coincidence technique has been applied to α-, β- as well as to γ-rays. An important part deals with the internal conversion process, which is a decay mode in competition with γ-ray emission. Several manifestations of the internal conversion process have been studied, especially its application to directional correlations. The atomic electrons ejected through interaction with the multipole field of the excited nucleus have actually for many years been used as reliable messengers of nuclear information. Besides being easier to deal with than ordinary gamma rays they carry some information which gamma rays do not, in that sense acting as some sort of prism analysing the radiation from the nucleus. The theory of the internal conversion process has been developed by Rose (4), Sliv and Band (5), Hager and Seltzer (6) and Pauli (7). As discussed in more detail below the electrons sometimes penetrate the nuclear domain therein interacting with currents and charges in a more familiar way, thus adding a nuclear structure dependent term to the conversion probability. It has been suggested that the conversion probability would be dependent on the degree of the static nuclear deformation. This effect is, however, very small (8) and up to now contradictory results have been reported (9,10,11). Alternatively the chemical environment seems to play a role in the conversion of the outer electrons (12).

Measurements of directional correlations utilizing conversion electrons unify the advantages of the gamma-gamma directional correlations with those of the pure electron intensity determinations giving both the parity of the involved radiations and the phase relations between them. This relationship, which is expressed in the sign of the multipole mixing ratio, has become more significant

after the phase consistent derivation of the angular distribution formulas by Rose and Brink (13). Hence the mixing ratio has become a physical quantity which can be compared in both magnitude and sign with predictions of the nuclear models.

Several results on mixing ratios obtained by means of directional correlations are reported in this thesis. The electron-gamma method has been extended to involve the different L electrons. The author has taken part in the calculations of the theoretical quantities needed to interpret such measurements, viz. the L particle parameters, by using matrix elements computed by Sliv and Band. These parameters were published in ref. (14) and initiated several new calculations for more extended regions of energies and atomic numbers (15,16,7).

This thesis contains the following papers.

1. F. FALK, S. TÖRNKVIST, J.E. THUN, H. SNELLMAN, K. SIEGBAHN and F. ASARO, A decoupling experiment on the α-γ correlation in Am^{243}. *Z. Physik 198* (1967) *106.*
2. J.E. THUN, S. TÖRNKVIST, F. FALK and F. KROPFF, The beta-gamma correlation in ^{198}Au. *Arkiv Fysik 25* (1964) *509.*
3. S. TÖRNKVIST and S. STRÖM, On the electron capture decay of ^{133}Ba to the 437 keV level in ^{133}Cs. *Arkiv Fysik 38* (1968) *261.*
4. J.E. THUN, S. TÖRNKVIST, S. STRÖM and F. FALK, L_2 electron-gamma correlation in ^{199}Hg. *Z. Physik 211* (1968) *352.*
5. S. TÖRNKVIST, J.E. THUN, S. STRÖM, R.G. ALBRIDGE and V. SCHMIDT, Directional correlation measurements with L_1 and L_2 conversion electrons of the 31 keV transition in ^{195}Pt. *Z. Physik 214* (1968) *214.*
6. J. E. THUN, S. TÖRNKVIST, F. FALK, H. SNELLMAN and F. KROPFF, The penetration matrix element of the 279 keV transition in Tl^{203}. *Physics Letters 8* (1964) *326.*
7. A. MARELIUS, H. PETTERSSON, S. TÖRNKVIST, S.E. HÄGGLUND and R. DUMITRESCU, Anomalous internal conversion of the 212 keV transition in ^{121}Te. *Arkiv Fysik 37* (1968) *435.*
8. S. TÖRNKVIST, L. HASSELGREN, J. E. THUN and A. MARELIUS, Nuclear structure effects in the particle parameters for the 84.2 keV transition in ^{231}Pa. *UUIP* 600. To be submitted to *Phys. Rev.*
9. J.E. THUN, S. TÖRNKVIST, F. FALK and H. SNELLMAN, Nuclear spectroscopy of Ba^{133m}. *Nucl. Phys. 67* (1965) *625.*

10. J.E. THUN, S. TÖRNKVIST, K. BONDE NIELSEN, H. SNELLMAN, F. FALK and A. MOCOROA, Levels and transitions in ^{133}Cs. *Nucl. Phys. 88* (1966) *289.*
11. S. TÖRNKVIST, S. STRÖM, J.E. THUN, V. SCHMIDT and N. BAADE, Internal conversion studies of the 113 keV transition in ^{177}Hf. *Nucl. Phys. A117* (1968) *336.*
12. Ö. NILSSON, S. TÖRNKVIST, G. MALMSTEN, J.E. THUN, S. HÖGBERG and N. BAADE, Internal conversion studies of the 114 keV transition in ^{175}Lu. *UUIP* 599. To be submitted to *Arkiv Fysik.*
13. S. TÖRNKVIST, S. STRÖM and L. HASSELGREN, K, L and M electron directional correlations in ^{123}Te. *UUIP 601.* To be submitted to *Arkiv Fysik.*
14. F. FALK, S. TÖRNKVIST, H. SNELLMAN and J.E. THUN, A versatile electron-gamma correlation spectrometer. *Nucl. Instr. and Meth. 49* (1967) *240.*

Paper 1 deals with the behavior of the directional correlation between α-particles and γ-rays when an external magnetic field is applied. The results have been confirmed later by Hutchinson (17).

Paper 2 gives the result of an investigation of the energy dependence of the β-γ directional correlation in ^{198}Au (the only even nucleus studied in this thesis).
Electron capture is a manifestation of beta decay. The relative probability for capture of K electrons was the object of the measurement reported in paper 3.

The excited levels in ^{199}Hg and ^{195}Pt seem to be good examples of the core-excitation mechanism. According to de Shalit (18) low-energy spectra of spherical odd-mass nuclei result from the coupling between the odd nucleon and the core of the even-even neighbouring nucleus. In the case of ^{199}Hg the two excited states at 158 keV and 208 keV, respectively are well described in terms of the coupling of the $p_{1/2}$ neutron to the 2^+ state of ^{198}Hg at 412 keV. Experimental quantites do not, however, support a similar picture for the levels in ^{195}Pt in the same clear cut way. Electromagnetic transition rates and nuclear magnetic moments from experiments are in conflict with the pure core-excitation predictions (19,20), but if configuration mixings are taken into account (21) certain experimental data can be explained (22). The papers 4 and 5 concern the transitions between the two members of the first doublet in ^{199}Hg and ^{195}Pt. The shell model classifies these transitions as l-forbidden ($\Delta l=2$) but the core-excitation model offers another interpretation according to which the transitions are of allowed spin-flip character.

An alternative explanation of the level structure of ^{195}Pt based on the asymmetric rotor model has been suggested by Hecht and Satchler (23). Consequently data on these transistions are of interest for checking the model descriptions. Unusually small E2/M1 mixing ratios were determined with high accuracy by means of L electron-gamma directional correlations. This technique has not earlier been used for this purpose because of theoretical as well as experimental difficulties.

As a consequence of the finite size of the nucleus there is a possibility that the wave functions for the atomic electrons are different from zero within the nuclear region, i.e. the electrons will penetrate the nucleus a small fraction of the time. While there they interact with the transition charges and currents in a more direct way than the nonpenetrating electrons. This means that an additional nuclear matrix element appears in the expression for the conversion electron transition probability. This penetration matrix element is generally small, but if the ordinary gamma ray matrix element is inhibited, penetration effects may be important. Inhibition of the gamma ray matrix element may occur for transitions which are *l*-forbidden according to the pure shell model. The fact that these transitions actually exist is explained by configuration mixings induced by short range correlations and collective quadrupole vibrations (24,25,26). A search for anomalies in the internal conversion process in this class of transitions is reported in the papers 6, 7 and 10.

Paper 6 deals with the 279 keV M1 + E2 transition in ^{203}Tl, for which the electron directional correlation coefficient is affected by dynamic nuclear structure effects. The ratio between the penetration matrix element and the gamma ray matrix element was determined to be $\lambda = 9 \pm 1$ thus excluding a second, earlier accepted solution $\lambda \sim 80$.
Additional information on this transition has appeared since the publication of paper 6. Gerholm et al. (27) re-analysed their old A_{22}-value taking the revised sign of the mixed particle parameter into account (28) and obtained $\lambda = 7.5 \pm 1.5$ Borisoglebskii (29) analysed the total M-shell conversion coefficient measured by Herrlander and Graham (30) with the result $\lambda = 7$. Karlsson et al. (31) measured the magnetic moment for the 279 keV level, and found $\mu = 0.16 \pm 0.05$ n.m. This value can be used to extract λ from the calculations by Tourneux. Computations based on the shell model and on the core-excitation model both gave $\lambda \sim 9$. (32).
In paper 7 experimental data on the K-conversion coefficient of the *l*-forbidden 212 keV transition in ^{121}Te could be explained only if penetration effects were assumed. The *l*-forbidden 81 keV transition in ^{133}Cs, which was subject to the investigation reported in paper 10, did not, however, show significant anomalous conversion behavior.

The M1 matrix element for transitions within rotational bands in deformed nuclei are expected to be proportional to $(g_K - g_R)$ where g_K and g_R are the particle and core gyromagnetic ratios, respectively. If these factors are equal or nearequal accidentally, the M1 transition will be slow. This is the case for the 113 keV transition in ^{177}Hf reported in paper 11. Due to the retardation of the M1 transition, penetration effects are expected to show up in the conversion process. No such effect was, however, found, a fact which can be explained by a strong E2 component in the transition.

The significance of the penetration matrix element is to some extent dependent on its connection with parity impurity of nuclear states. The current-current hypothesis by Feyman and Gell-Mann (33) predicts the existence of a weak parity non-conserving nuclear force. As in the case of penetration matrix elements parity impurities are observable in such cases where the regular process is hindred, e.g. retarded electromagnetic transitions. For M1 transitions experimentally determined λ values make it possible to predict at least the sign of the ratio between the nuclear matrix element of the irregular parity-forbidden E1 and the regular M1 process. Such calculations have been performed by Wahlborn (34) for ^{181}Ta and by Szymanski for ^{203}Tl (35).
The interference of the E1 and M1 matrix elements implies circular polarization of the gamma rays. The degree of polarization has been determined for some hindered M1 transition among them the 279 keV transition in ^{203}Tl. (36,37). Much effort has been devoted to find new experimental methods for observing parity admixtures in nuclear states (38).

The penetration effect in the internal conversion of E1 transitions can be expressed in terms of a charge parameter ξ and a current parameter η (39). Often, however, the weighting of ξ is very small and the anomaly factor can be described only by η. This current parameter has been measured for the 84.2 keV transition in ^{231}Pa, reported in paper 8.

Paper 9 reports on the level structure of ^{133m}Ba. Energies, lifetimes, a conversion coefficient and conversion ratios were measured and the transition probability for the 12.3 keV *l*-forbidden M1 transition was computed. Paper 10 deals with the subsequent decay ^{133}Ba. Level energies of ^{133}Cs were determined with greater accuracy than previous measurements. The results of this part of the investigation have been listed as standard energies intended for calibration use (40). Furthermore gamma and electron intensities, internal conversion coefficients, and particle parameters were measured. During the two years since paper 10 was published an enormity of data has been reported on this isotope (41—59). Practically all data given have been confirmed with two exceptions: The K-conversion coe-

fficient of the 161 keV transition has been shown to be too high. This is probably due to an underestimation of the statistical error in the electron intensity. Modern Si(Li) detectors used in later investigations (48,49) are evidently more suitable for detecting this weak electron line. The second exception is the relative K capture probability in the decay of ^{133}Ba to the 437 keV level in ^{133}Cs. This has, however, been remeasured by the author by means of a more accurate method. This later measurement, which is presented in paper 3, yielded a value in agreement with those by other authors.

One of the most fascinating features of the structure of the excited levels of ^{133}Cs presented in paper 10, was the collective character of the 53 keV transition. This finding has later been confirmed by Blasi et al. (30) who also showed that the Kisslinger-Sorensen model was able to account at least qualitative for this behavior.
It has been shown that in the region where Z is just above 50 and N just below 82 there exists an area of nuclear deformation in addition to those at $150 < A < 190$ and $A > 210$. The measured ground state spin for the cesium isotopes with neutron number 72, 74, 76, 78, 80 and 82 are respectively 1/2, 1/2, 5/2, 7/2, 7/2, 7/2. The value 7/2 for $N = 82$ is expected from the g7/2 spherical shell model spin. A sufficiently large ellipsoidal deformation of the nuclear potential tend, however, to quench the orbital angular momentum of a particle so that the spin 1/2 lies lowest. This happens for $N = 72$ and 74.
Despite that ^{133}Cs ($N=78$) has a ground state spin of 7/2 and consequently lies on the border of this region of weak deformation the experimental data on transitions between the higher levels call for some collective nature of excitation. Observation of a spin 19/2 three quasiparticle excitation in ^{135}Cs (60) and a negative parity level in ^{133}La (61) represent other manifestations of collective behavior in this region.
The fact that ^{133}Cs has an extraordinary small quadrupole moment in its ground state might indicate that the excitations are basically vibrational. Anyway ^{133}Cs seems to lie in a region where many nuclear theories give contributions to the understanding but none of them are completely satisfactory.

Extensive studies of the internal conversion of two transitions within the lowest rotational band of the deformed nuclei ^{177}Hf and ^{175}Lu respectively, are reported in the papers 11 and 12. Special attention was paid to the conversion process itself, thus, in the ^{175}Lu case revealing a small discrepancy between theory and experiment. Paper 13 concerns three directional correlations measured on the same cascade in ^{123}Te. Recently calculated particle parameters for M electrons were for the first time used to analyse the experimental data.

Most of the experiments mentioned above have been performed by means of an electron-gamma directional correlation spectrometer. This instrument is described in paper 14.

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